Biomedical Sensor Systems

Laboratory

Laboratory Tutorial: Oscillation Measurement

Place: BMT02002, Stremayrgasse 16, 2.OG

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Short Description:

In this lab students will perform oscillation measurements implemented by a piezo transducer and appropriate amplifier circuits. The signals will be analysed and interpreted using a storage oscilloscope.

Learning Objectives:

The students are able to …

- … understand the principles of sensors and amplifiers
- … design appropriate amplifier curcuits for given problems
- … handle oscilloscopes and understand the functional principles
- … to solve second-order differential equations

Content

1. Theory

1.1. Analogue measurement

Why are amplifiers needed?

→ measured potentials and currents often low
→ sensor elements often load-sensitive
→ tapping/transforming of measured variables

Requirements:

- low response to measured variable
- high resolution
  also little current or voltage signals and changes should be measurable
- defined response characteristics
  the output signal should uniquely depend on the input signal
- good dynamic behavior
  the output signal should follow the input signal as fast as possible

- output stable and insensitive to response
  ouput signals should not be changed by following measurement instruments

1.1.1. Operational Amplifier „OpAmp“

Amplifiers are made up of one or more OpAmps. Figure 1 shows the simplified internal wiring of an OpAmp.

Differential input stage (yellow): differential amplifier with two inputs and constant current source; converts small potential differences to a proportional output current.

Amplifier stage (orange): transforms the small input current into a high output voltage; sets high off-load voltage amplification; frequency-dependent feedback of the capacitor ensures stability and determines the cutoff frequency.

Output stage (blue): often a push-pull, no voltage amplification, acts as current driver for the output, small output resistor which enables a high output current.

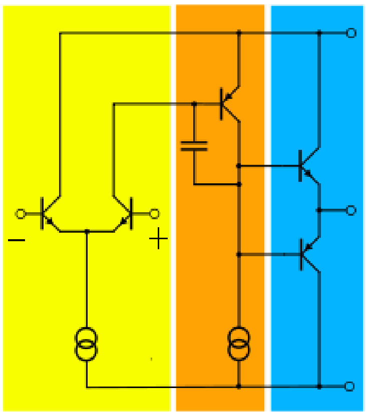
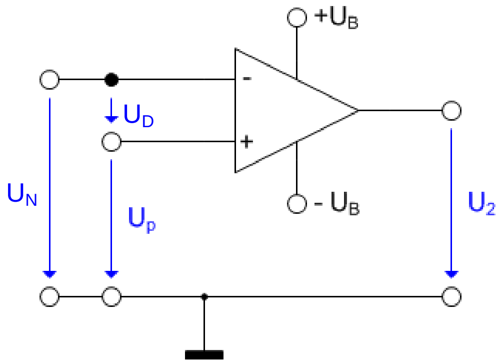


Figure 1: Simplified internal wiring of an OpAmp

Ideal OpAmps are assumed to have a voltage-controlled power supply with open load voltage gain $V_0 \to \infty$ (see Figure 2). **Real** OpAmps have a open loop voltage gain of about 10^4 to 10^7.



$$u_A = V_0.(u_P - u_N) = V_0.u_D$$

ideal: $V_0 \to \infty$

real: $V_0 \approx 10^4$ to 10^7

Figure 2: Equivalent curcuit diagram OpAmp

The transfer characteristic of an OpAmp is illustrated in Figure 3. u_A is limited by the supply voltage U_B → so u_{Amax} is always smaller than U_B.

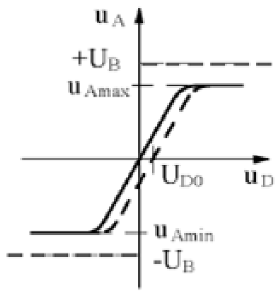


Figure 3: Transfer characteristic OpAmp, U_{D0}: input offset voltage

1.2. Transducers, sensors and actuators

Transducer convert one form of energy to another energy form. If a transducer converts a measurable quantity (mechanical, thermal,…) into an electrical signal (voltage, current) we will call it a sensor. In turn, a transducer is referred to as an actuator if electrical signals are converted into other energy forms, for example machanical movement, light or sound.

A sensor is the primary element in a measurement chain. They can be differentiated into active and passive sensors. Active sensors convert non-electrical energy into electrical energy (voltage) without auxiliary voltage. Passive sensors change their electrical properties under the influence of non-electrical variables. In Table 1 are listed some active and passive sensors and their variables.

Active sensors	**non-electrical parameter**	
thermal element	temperature, radiation	
photo element	light, temperature	
electrochemical element	ph-Value, redox potential	
piezo sensor	force, pressure, tension, acceleration, temperature	
induction sensor	rate of rotation, acceleration	
Passive sensors	**influenced electrical parameter**	**non-electrical parameter**
potentiometer	ohmic resistance	length, angle
strain gauge	ohmic resistance	force, pressure, length, angle, strain, torsion
photo resistor, photo transistor, photo diode	ohmic resistance	light variables
resistance thermometer	ohmic resistance	length, angle
transformer	magnetic coupling	length, angle
Hall probe	voltage	length, angle
induction sensor	inductance	length, angle
capacitive sensor	capacitance	length, angle
magnetic sensor	magnetic field	length, angle

Table 1: Overview active and passive sensors

1.1.2. Piezo sensors

Piezoelectric effect

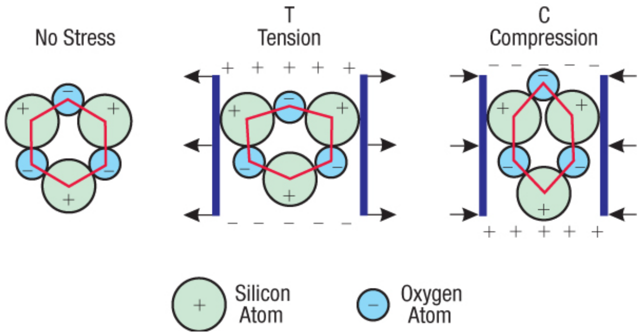


Figure 4: Piezoelectric effect in Quartz

Figure 4 shows the piezoelectric effect of a quartz molecule. Mechanical deformation like tension or compression cause a charge shifting and thereby a voltage. Reversely, an applied voltage lead to a deformation of the material. So, piezoelectric crystals and ceramics can be both, an actuator as well as a sensor.

Piezo Sensors

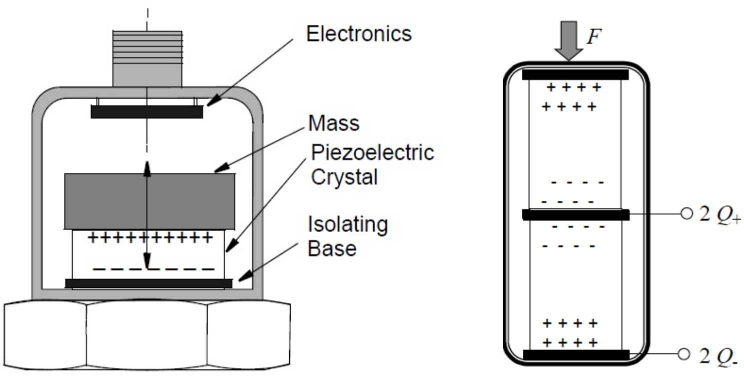


Figure 5: Piezo Sensor for acceleration

Piezo sensors (see Figure 5) can be used to determine a variety of physical variables (e.g. pressure, acceleration, temperature, strain or force). The function principles are mainly based on the longitudinal effect, transversal effect and shear effect. Figure 5 illustrates the longitudinal effect, caused by two crystals put together, which results in a force meter. The charge is proportional to the applied force, at least in a limited area.

The charge shift is characterised by displacement of the shift flux density D

$$D = \frac{Q}{A} \tag{1}$$

$$Q = k_p . F \tag{2}$$

where Q is the charge and A the area. The coefficient k_p depicts the piezoelectric constant, also called piezo modul and F is the force.

The charges are not directly measurably and have to be converted to a proportional voltage U_q by a capacitor. Thereby charge Q can be written as

$$Q = C.U_q \Rightarrow U_q = \frac{Q}{C} = \frac{k_p.F}{C} \tag{3}$$

Therefore amplifiers with a great high-ohmic input are applicable, so called electrometer amplifiers (non-inverting amplifier) and charge amplifiers.

Electrometer amplifier

The input resistance of the amplifier R_e as well as the loss resistance R_p have to be very high-ohmic. Otherwise the charge would be compensated quickly. The time constant of the measurement setup as shown in Figure 6 can be calculated as follows

$$\tau = R_{ges} C_{ges} = \left(\frac{R_e . R_p}{R_e + R_p} \right) . (C_0 + C_L + C_e) \qquad R_e \parallel R_p \rightarrow \infty \tag{4}$$

and the output voltage U_a is

$$U_a = U_q \left(1 + \frac{R_2}{R_1} \right) = \frac{Q}{C_{ges}} . \left(1 + \frac{R_2}{R_1} \right) = F . \frac{k_p}{C_{ges}} . \left(1 + \frac{R_2}{R_1} \right) \tag{5}$$

Attend:

- U_q = f(F)
- unavoidable, external switching capacities lower sensitivity

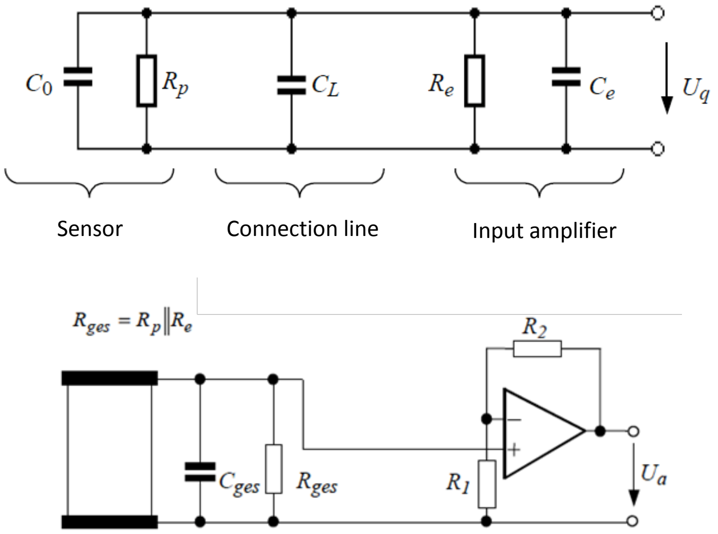


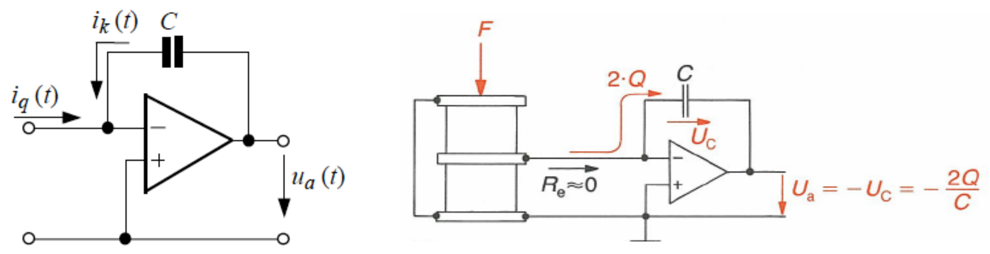
Figure 6: Piezo sensor with electrometer amplifier

Charge amplifier

The charge amplifier converts the charge quantity, proportional to the force, into the voltage u_a. The current $i_q(t)$ is directly derived from the charge shifting and the current $i_k(t)$ from the output voltage of the OpAmp, differentiated by capacitor C. The equations for $i_q(t)$ and $i_k(t)$ can be written as follows

$$i_q(t) = \frac{dQ}{dt} \tag{6}$$

$$i_k(t) = C.\frac{du_a(t)}{dt} \tag{7}$$



a) b

Figure 7: a) Equivalent curcuit digram charge amplifier b) Piezo sensor with charge amplifier

As shown in Figure 7 a), $i_q(t) + i_k(t) = 0$. After integration, the equation for u_a of the charge amplifier is given by

$$u_a(t) = -\frac{1}{C}\int_0^T iq(t)dt = -\frac{Q}{C} = -\frac{k_p.F}{C} \qquad (8)$$

For u_a instead of the parasitic capacitances (C_0, C_L, C_e) the only decisive capacitance is the measuring capacitance C. A disadvantage is the restriction to the measurement of alternating parameters, because of charge changes over time.

1.3. Oscilloscope

1.3.1. Functional principle

Oscilloscopes are used to display the change of an electrical signal over time. Basically, all procedures which can be reproduced as a voltage time curve can also be displayed by an oscilloscope. The observed waveform can be analyzed for shape parameters such as amplitude, frequency, rise time, time interval, phase shift, distortion and others.

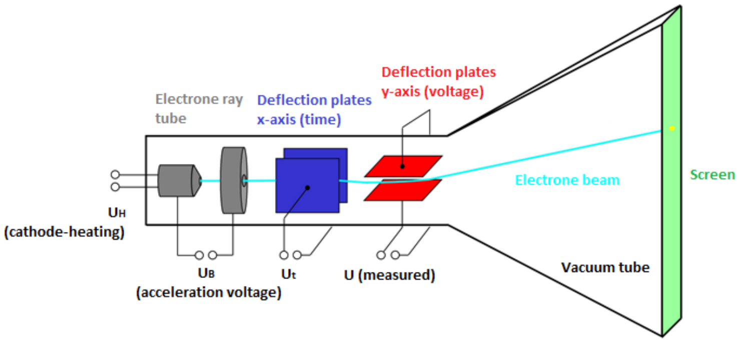


Figure 8: Basic construction analogue oscilloscope

Before the advent of digital electronics, analogue oscilloscopes (Figure 8) used electrode ray tubes to display the signals. Thereby, an electron emitter generates free electrons which get focused and accelerated by high voltage U_B. The measured signal gets amplified and is used to diffract the electron beam by deflection plates. Finally the deflected electrons come upon the screen and induce the fluorescing screen material to light up.

In principle, a digital oscilloscope works like an analogue, but the measured signals get converted by an A/D transducer before processing and the signals can be stored for further investigations. The digital-analog conversion also makes many things easier by, for example, implemented analysis software (FFT, average,…), autoset-autorange function, pre-trigger and allows the recording of slow signal curves. Regulary several A/D transducers are used to illustrate high frequency signals still accurate. Particularly important, in order to be able to represent signals accurate and to avoid aliasing, the conditions of the **sampling theorem** have to be observed.

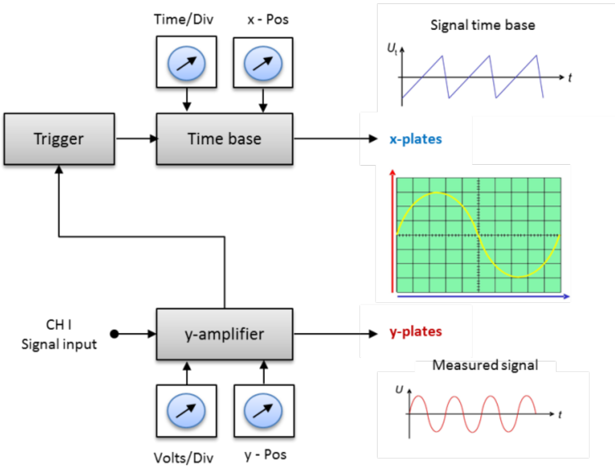


Figure 9: Functional principle oscilloscope

To get a temporal representation of the input signal, the light point has to move with constant speed, horizontal along the screen. This happens due to a sawtooth voltage U_t generated by the time base (see Figure 9). During the falling edge of U_t the light point is faded out. The rise time of this voltage sets the time dimension of the x-axis, coefficient K_t (e.g. 0,2 µs/raster element) give the time per raster element or cm of the x-axis.

The **Trigger** starts the sawtooth voltage, which generates the stationary image. To get the same sequence in all periods, the measured signal U and U_t have to run paired. Therfore a trigger level is used, whereby the sawtooth voltage gets started if voltage U exceeds this level.

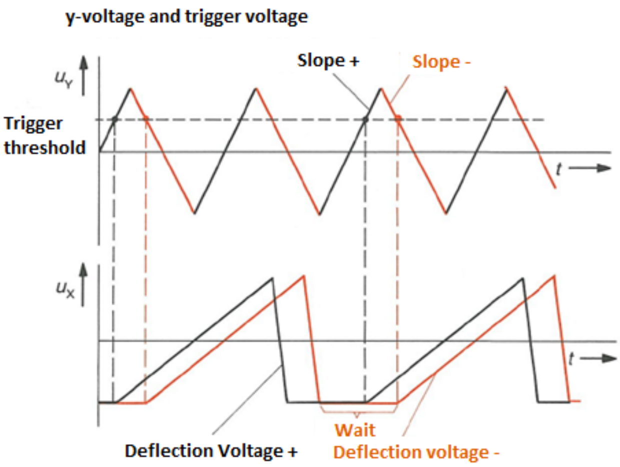


Figure 10: Trigger function

x-y mode: most modern oscilloscopes have several inputs for voltages which can be used to plot one varying voltage versus another. In x-y mode the oscilloscope have the same deflection sensitivity for both the x- and y- direction. This is especially useful for graphing I-V curves (current versus voltage characteristics) for components such as diodes. Lissajous figures for example are used to track phase differences between multiple input signals and can be used for frequency measurement as illustrated in Figure 11.

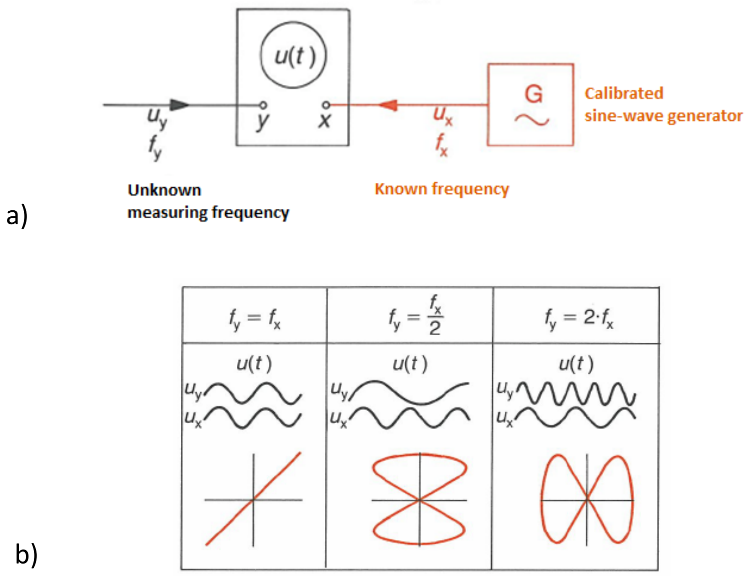


Figure 11: a) Measuring setup for frequency measurement. b) Lissajous figures.

1.3.2. Setup and basic functions

The basic oscilloscope is typically divided into four sections: the display, vertical controls, horizontal controls and trigger controls. In addition to the screen, most display sections are equipped with three basic controls: a focus knob, an intensity knob and a beam finder button.

The vertical section controls the amplitude of the displayed signal. This section carries a Volts-per-Division (Volts/Div) selector knob, an AC/DC/Ground selector switch and the vertical (primary) input for the instrument. Additionally, this section is typically equipped with the vertical beam position knob.

The horizontal section controls the time base or "sweep" of the instrument. The primary control is the Seconds-per-Division (Sec/Div) selector switch. Also included is a horizontal input for plotting dual X-Y axis signals. The horizontal beam position knob is generally located in this section.

The trigger section controls the start event of the sweep and can be set to automatically restart after each sweep or it can be configured to respond to an internal or external event. The principal controls of this section will be the source and coupling selector switches. An external trigger input (EXT Input) and level adjustment will also be included.

2. Preparatory activities for the lab

As preparatory activities for the lab you should:

I. dimension and complete appropriate amplifier circuits for oscillation measurment with a piezo element (see section 2.1). You should be able to describe primarly differences and advantages as well as disadvantages of the circuits.

II. mathematically establish the mathematical descriptive equation of a (weak) damped oscillation (see section 2.2)

III. get familiar with the functional principles of a oscilloscope

2.1. Dimensioning and completion appropriate amplifier circuits

Figure 12 and Figure 13 illustrate incomplete circuitries of a charge and electrometer amplifier. Dimension and complete the circuitry by adding resistors under the following conditions:

- the sensor will be the miniature-accelerometer sensor KS93, with charge changing proportional to acceleration
- measured frequencies are in the range of 40 to 80 Hz
- a LM324 will be used as operational amplifier
- capacitors are available in the range of 1 pF to 47 pF
- resistors up to 10 MΩ are available

useful hints:
- you can find all data sheets in the appendix
- consider, the input of the op-amp always should be on defined levels
- also consider the power supply of the LM324

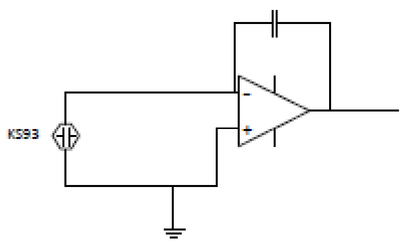


Figure 12: Incomplete charge amplifier

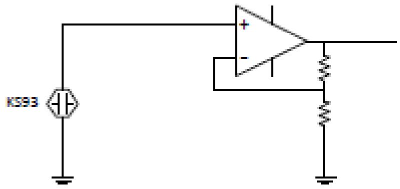


Figure 13: Incomplete electrometer amplifier

2.2. Mathematical model of a (weak) damped oscillation

Together with the amplifier circuit the piezo sensor provides an electrical signal, sufficient to a damped oscillication. During the lab you will be concerned with oscillation progressions u(t), that amplitudes A subsides over the time. A (linear) signal progression can be described by the following mathematical equation:

$$u(t) = A.e^{-\frac{t}{\tau}}.\left[\cos(\omega t) + \frac{1}{\omega.\tau}.\sin(\omega.t)\right] \tag{9}$$

where A is the amplitude at time t = 0, ω the angular frequency of the oscillation and τ the subside constant. The differential equation of a free damped oscillation is given by

$$u'' + \frac{k_1}{m}u' + \frac{k_2}{m}u = 0 \tag{10}$$

where u(t) is the deflection at time t, k_1 is the damping coefficient, k_2 the spring constant and m the mass of the swinging body. The right side of the equation is set to 0, because of an free oscillation without an exterior time excitation. A quite handy substitution with

$$\frac{2}{\tau} = \frac{k_1}{m} \text{ and } \omega^2 = \frac{k_2}{m}$$

and the consideration of the initial conditions u(t=0) = u_0 = A (deflection at time t=0) as well as u'(t=0 = u'_0 = 0 (the body will not be given an initial speed) lead – after appropriate computation – to equation 1.

Execute that computation and demonstrate understandable, that equation 9 is the result of equation 10 in regards to

- initial conditions
- the fact that it's a weak damped oscillation
- correlating given substitutions

Please note: The calculation should be performed **solely** in the time domain without using laplace transforms.

useful hints:

Make use of the fact that it's a weak damped oscillation where ω can be set as

$$\omega >> \frac{1}{r^2}$$

consistently you can set expressions like

$$\sqrt{\frac{1}{\tau^2} - \omega^2} = j.\sqrt{\omega^2 - \frac{1}{r^2}} \cong j.\sqrt{\omega^2} = j.\omega$$

On the basis of your measured results you will determine paramters A, ω and τ. In advance, plan ahead how the determination respectively the calculation can be carried out. Keep in mind that you have to expect corresponding fluctuation ranges for ω and τ. Hence you should make for instance an averaging over several periods.

For this purpose, exemplary assume an oscillation as shown in Figure 14:.

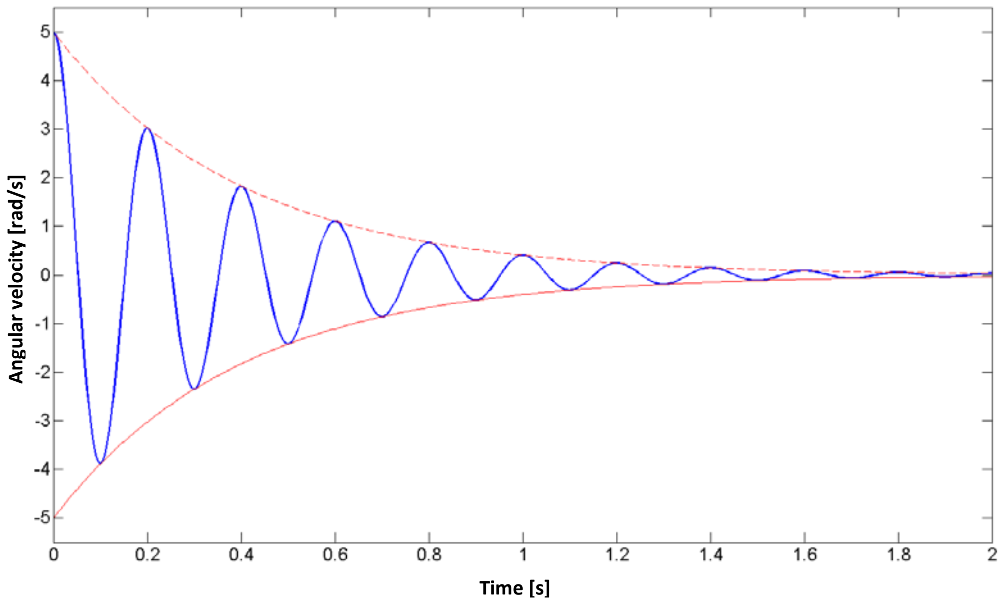


Figure 14: Example of an oscillation course u(t) out of equation 9, with decaying amplitude over time ($A.e^{-\frac{t}{\tau}}$). In this case paramter A = 5 rad/s, τ = 2,5 s and ω = 5 1/s. The red lines show the contour of the oscillation.

2.3. Oscilloscope

The signals will be measured with a digital storage oscilloscope. Consider, wheter the signals could be also measured by an analogue oscilloscope or not. Explain your statement.

3. Implementation in the lab

3.1. Charge amplifier

Tension the ruler at 10 cm and 20 cm. Deflect it slightly first (1) and greater secondly (2) and record the oscillation until the ruler is resting again.

Please note: in case of large oscillations the saturation region can be reached depending on the dimension of your charge amplifier.

Conduct and answer following tasks and questions for both deflections:

a) Implement your designed charge amplifier circuit on a patch panel.
b) Metrologically determine the frequency of the fundamental oscillation with the help of an oscilloscope.
c) Does the frequency remain constant?
d) Determine the damping coefficient under assuming a damped harmonic oscillation.
e) Additionally, switch a capacitor parallel to the input. The capacitor should simulate a changed interconnected capacitance. Are there changes in the output signal? Justify your observation.

3.2. Electrometer amplifier

Repeat tasks a) to e) of 3.1 with an electrometer amplifier.

4. Appendix

Miniatur-Beschleunigungsaufnehmer
Miniature Accelerometers

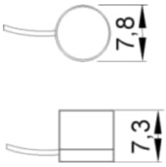
1.6.2
Sensoren
Sensors
KS91
KS93

Eigenschaften

- Für leichte Messobjekte
- KS91 in Subminiaturausführung
- KS91 mit IEPE-Spannungsausgang
- KS93 mit Ladungsausgang
- Hoher Dynamikbereich
- Hohe Resonanzfrequenzen
- KS93 mit auswechselbarem Kabel
- KS93 mit M3-Befestigungsgewinde im Boden
- KS91 mit isoliertem Boden gegen Erdschleifen

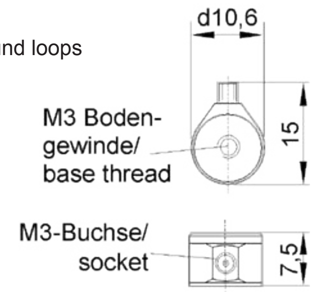
Properties

- For light test objects
- KS91 in subminiature design
- KS91 with IEPE voltage output
- KS93 with charge output
- Wide dynamic range
- High resonant frequency
- KS93 with replaceable cable
- KS93 with M3 mounting thread in base
- KS91 with insulated base avoiding ground loops

KS91

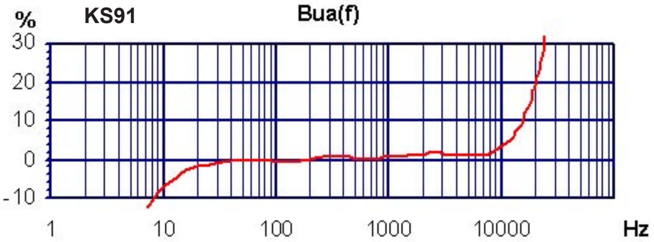
KS93

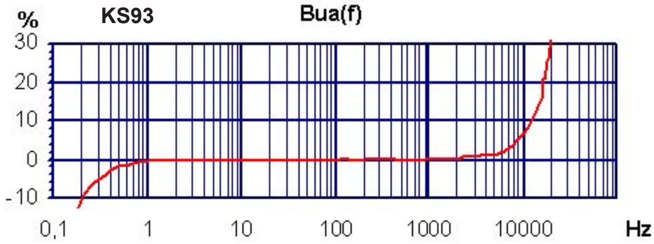


		KS91	KS93	
Ausgang • Output		IEPE	Ladung • Charge	
Piezosystem • Piezo design		Scherprinzip • Shear design		
Ladungsübertragungsfaktor • Charge sensitivity	B_{qa}	-	5 ± 20%	pC/g
Spannungsübertragungsfaktor • Voltage sensitivity	B_{ua}	10 ± 20%	-	mV/g
Messbereich • Range	a_+ / a_-	700	6000	g
Bruchbeschleunigung • Destruction limit	a_{max}	8000	8000	g
Linearer Frequenzbereich • Linear frequency range	$f_{3\,dB}$ $f_{10\,\%}$ $f_{5\,\%}$	4 .. 26 000 8 .. 15 000 12 .. 10000	22 000 12 000 9000	Hz Hz Hz
Resonanzfrequenz • Resonant frequency	f_r	> 50 (+25 dB)	> 42 (+25 dB)	kHz
Querrichtungsfaktor • Transverse sensitivity	Γ_{90MAX}	< 5	< 5	%
Eigenrauschen (Effektivwert; 10 Hz - 50 kHz) • Residual noise (RMS; 10 Hz - 50 kHz)	$a_{n\,wide\,band}$	< 3000	-	µg (Hz)
Rauschdichten • Noise densities 10 Hz 100 Hz	a_{n1} a_{n2}	100 10	- -	µg/√Hz µg/√Hz
Konstantstromversorgung • Constant current supply	I_{CONST}	2 .. 20	-	mA
Arbeitspunktspannung bei I_{CONST} = 4 mA • Output bias voltage at I_{CONST} = 4 mA	U_{BIAS}	10 .. 12 V	-	V
Ausgangsimpedanz bei I_{CONST} = 4 mA • Output impedance at I_{CONST} = 4 mA	r_{OUT}	<50	-	Ω
Kapazität ohne Kabel • Capacitance without cable	C_i	-	0,4	nF
Verhalten gegenüber Umgebungsbedingungen • Environmental characteristics				
Arbeitstemperaturbereich • Operating temperature range	T_{min}/T_{max}	-20 / 120	-20 / 150	°C
Temp.-koeffizient der Lad.-Empfindl. • Temp. coefficient of charge sensitivity	$TK(B_{qa})$	-	0,06	%/K
Temp.-koeffizient der Spg.-Empfindl. • Temp. coefficient of voltage sensitivity	$TK(B_{ua})$	-0,2		
Temp.-koeffizient der Kapazität. • Temp. coefficient of capacitance	$TK(C_i)$	-	0,14	%/K
Temperatursprungempfindlichkeit • Temperature transient sensitivity	b_{aT}	2	3	ms^{-2}/K
Messobjektdehnungsempfindlichkeit • Base strain sensitivity	b_{aS}	-	0,2	$ms^{-2}/\mu D$
Magnetfeldempfindlichkeit • Magnetic field sensitivity	b_{aB}	-	1,3	ms^{-2}/T
Mechanische Daten • Mechanical data				
Masse ohne Kabel • Weight without cable	m	1,0 / 0,035	2,7 / 0,095	g / oz
Gehäusematerial • Case material		Alu, Edelstahl Alum. stainl. st.	Titan, Edelstahl Titan., stainl. st.	
Kabelanschluss • Cable connection		radial	radial	
Anschlusskabel / -buchse • Connection cable / socket		fest / integral(1)	Subminiat. M3	
Befestigung • Mounting		Kleben / adhesive	M3 Gew. / thread	
Isolation • Insulation		ja / yes	nein / no	

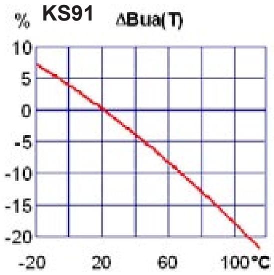
(1) KS91 hat 1,5 m fest angebrachtes Kabel mit UNF 10-32-Stecker
KS91 has 1.5 m integral cable with UNF 10-32 plug

Typischer Frequenzgang
Typical Amplitude Response

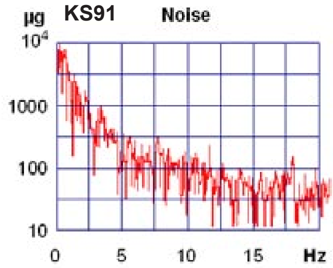




Temperaturverhalten
Temperature Characteristics



Rauschverhalten
Noise Characteristics



Passendes Zubehör • Suitable Accessories

	KS91	KS93
Anschluss-zubehör	• **010-UNF-BNC-5/10**: Kabel UNF 10-32 / BNC; 5 / 10 m lang (zur Verlängerung) • **016**: Kupplung für 2 UNF 10-32-Stecker • **017**: Adapter UNF 10-32 / BNC (männlich) • **117**: Adapter UNF 10-32 / BNC (weiblich) • **025**: Adapter UNF 10-32 / TNC (männlich)	• **009-SUB-UNF-1,5**: Störarmes Kabel Subminiatur / UNF 10-32; 1,5 m lang;120 °C • **009/T-SUB-UNF-1,5**: Störarmes Kabel Subminiatur / UNF 10-32; 1,5 m lang; 200 °C • **010-UNF-BNC-10**: Störarmes Kabel UNF 10-32 / BNC; 5 / 10m lang (zur Verlängerung) • **016**: Kupplung für 2 UNF 10-32-Stecker • **017**: Adapter UNF 10-32 / BNC (männlich) • **117**: Adapter UNF 10-32 / BNC (weiblich) • **025**: Adapter UNF 10-32 / TNC (männlich)
Connection accessories	• **010-UNF-BNC-5/10**: cable UNF 10-32 / BNC; 5 / 10 m long (for extension) • **016**: Coupler for 2 UNF 10-32 plugs • **017**: Adapter UNF 10-32 / BNC (male) • **117**: Adapter UNF 10-32 / BNC (female) • **025**: Adapter UNF 10-32 / TNC (male)	• **009-SUB-UNF-1,5**: Low noise cable Subminiature / UNF 10-32; 1.5 m long; 80 °C • **009/T-SUB-UNF-1,5**: Low noise cable Subminiature / UNF 10-32; 1.5 m long; 200 °C • **010-UNF-BNC-10**: Low noise cable UNF 10-32 / BNC; 5 / 10 m long (for extension) • **016**: Coupler for 2 UNF 10-32 plugs • **017**: Adapter UNF 10-32 / BNC (male) • **117**: Adapter UNF 10-32 / BNC (female) • **025**: Adapter UNF 10-32 / TNC (male)
Befestigungs-zubehör	• **002:** Klebewachs	• **002:** Klebewachs • **021:** Gewindestift M3 • **106**: Isolierflansch M3 • **129**: Isolierendes Klebepad M3 • **022:** Gewindeadapter M3 / M5 • **108:** Haftmagnet M3 • **130**: Triaxial-Befestigungswürfel M3 • **140**: Handgriffadapter für gekrümmte Oberflächen
Mounting accessories	• **002:** Adhesive wax	• **002:** Adhesive wax • **021:** Mounting stud M3 • **106**: Insulating flange M3 • **129**: Insulating adhesive pad M3 • **022:** Thread adapter M3 / M5 • **108:** Magnetic base M3 • **130**: Triaxial mounting cube M3 • **140**: Handle adapter for curved surfaces

Bestellinformation • Ordering Information

KS93/01: Aufnehmer mit Zubehöretui; Inhalt: Kabel 009-SUB-UNF-1,5, Adapter 017, Gewindestift 021, Klebewachs 002, Isolierflansch 106, Klebepad 129, Haftmagnet 108, Bedienungsanleitung, Kennblatt

Sensor with accessories kit including cable 009-SUB-UNF-1,5, adapter 017, mounting stud 021 adhesive wax 002, insulating flange 106, adhesive pad 129, magnetic base 108, instruction manual, data sheet

KS91; KS93: Aufnehmer mit Kennblatt
Sensor with data sheet

Hinweis: Auf Wunsch liefern wir unsere Aufnehmer mit einem kostengünstigen DKD-Kalibrierzertifikat. Preise auf Anfrage.

Note: Our transducers can be supplied with an attractively priced calibration certificate of DKD. Prices on demand.

Änderungen vorbehalten.

Specifications subject to change without prior notice.

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Email: Info@MMF.de

Ausgabe / Edition: 01/12

LM324, LM324A, LM224, LM2902, LM2902V, NCV2902

Single Supply Quad Operational Amplifiers

The LM324 series are low–cost, quad operational amplifiers with true differential inputs. They have several distinct advantages over standard operational amplifier types in single supply applications. The quad amplifier can operate at supply voltages as low as 3.0 V or as high as 32 V with quiescent currents about one–fifth of those associated with the MC1741 (on a per amplifier basis). The common mode input range includes the negative supply, thereby eliminating the necessity for external biasing components in many applications. The output voltage range also includes the negative power supply voltage.

- Short Circuited Protected Outputs
- True Differential Input Stage
- Single Supply Operation: 3.0 V to 32 V (LM224, LM324, LM324A)
- Low Input Bias Currents: 100 nA Maximum (LM324A)
- Four Amplifiers Per Package
- Internally Compensated
- Common Mode Range Extends to Negative Supply
- Industry Standard Pinouts
- ESD Clamps on the Inputs Increase Ruggedness without Affecting Device Operation

MAXIMUM RATINGS (T_A = +25°C, unless otherwise noted.)

Rating	Symbol	LM224 LM324, LM324A	LM2902, LM2902V	Unit
Power Supply Voltages				Vdc
Single Supply	V_{CC}	32	26	
Split Supplies	V_{CC}, V_{EE}	±16	±13	
Input Differential Voltage Range (Note 1)	V_{IDR}	±32	±26	Vdc
Input Common Mode Voltage Range	V_{ICR}	–0.3 to 32	–0.3 to 26	Vdc
Output Short Circuit Duration	t_{SC}	Continuous		
Junction Temperature	T_J	150		°C
Storage Temperature Range	T_{stg}	–65 to +150		°C
Operating Ambient Temperature Range	T_A			°C
LM224		–25 to +85		
LM324, 324A		0 to +70		
LM2902			–40 to +105	
LM2902V, NCV2902			–40 to +125	

1. Split Power Supplies.

ON Semiconductor®

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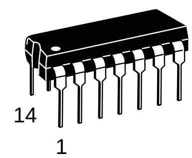
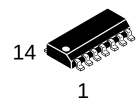
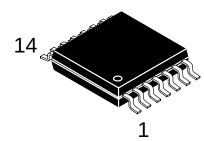


PDIP–14
N SUFFIX
CASE 646

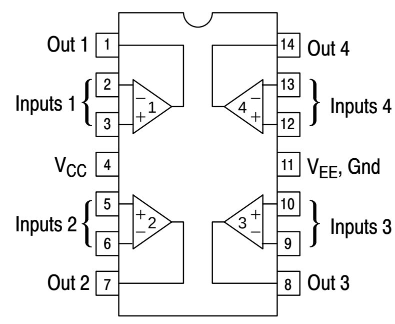


SO–14
D SUFFIX
CASE 751A



TSSOP–14
DTB SUFFIX
CASE 948G

PIN CONNECTIONS



(Top View)

ORDERING INFORMATION

See detailed ordering and shipping information in the package dimensions section on page 9 of this data sheet.

DEVICE MARKING INFORMATION

See general marking information in the device marking section on page 10 of this data sheet.

ELECTRICAL CHARACTERISTICS (V_{CC} = 5.0 V, V_{EE} = Gnd, T_A = 25°C, unless otherwise noted.)

Characteristics	Symbol	LM224			LM324A			LM324			LM2902			LM2902V/NCV2902			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage V_{CC} = 5.0 V to 30 V (26 V for LM2902, V), V_{ICR} = 0 V to V_{CC} –1.7 V, V_O = 1.4 V, R_S = 0 Ω	V_{IO}																mV
T_A = 25°C		–	2.0	5.0	–	2.0	3.0	–	2.0	7.0	–	2.0	7.0	–	2.0	7.0	
$T_A = T_{high}$ (Note 2)		–	–	7.0	–	–	5.0	–	–	9.0	–	–	10	–	–	13	
$T_A = T_{low}$ (Note 2)		–	–	7.0	–	–	5.0	–	–	9.0	–	–	10	–	–	10	
Average Temperature Coefficient of Input Offset Voltage $T_A = T_{high}$ to T_{low} (Notes 2 and 4)	$\Delta V_{IO}/\Delta T$	–	7.0	–	–	7.0	30	–	7.0	–	–	7.0	–	–	7.0	–	μV/°C
Input Offset Current	I_{IO}	–	3.0	30	–	5.0	30	–	5.0	50	–	5.0	50	–	5.0	50	nA
$T_A = T_{high}$ to T_{low} (Note 2)		–	–	100	–	–	75	–	–	150	–	–	200	–	–	200	
Average Temperature Coefficient of Input Offset Current $T_A = T_{high}$ to T_{low} (Notes 2 and 4)	$\Delta I_{IO}/\Delta T$	–	10	–	–	10	300	–	10	–	–	10	–	–	10	–	pA/°C
Input Bias Current	I_{IB}	–	–90	–150	–	–45	–100	–	–90	–250	–	–90	–250	–	–90	–250	nA
$T_A = T_{high}$ to T_{low} (Note 2)		–	–	–300	–	–	–200	–	–	–500	–	–	–500	–	–	–500	
Input Common Mode Voltage Range (Note 3) V_{CC} = 30 V (26 V for LM2902, V)	V_{ICR}																V
T_A = +25°C		0	–	28.3	0	–	28.3	0	–	28.3	0	–	24.3	0	–	24.3	
$T_A = T_{high}$ to T_{low} (Note 2)		0	–	28	0	–	28	0	–	28	0	–	24	0	–	24	
Differential Input Voltage Range	V_{IDR}	–	–	V_{CC}	–	–	V_{CC}	–	–	V_{CC}	–	–	V_{CC}	–	–	V_{CC}	V
Large Signal Open Loop Voltage Gain R_L = 2.0 kΩ, V_{CC} = 15 V, for Large V_O Swing	A_{VOL}	50	100	–	25	100	–	25	100	–	25	100	–	25	100	–	V/mV
$T_A = T_{high}$ to T_{low} (Note 2)		25	–	–	15	–	–	15	–	–	15	–	–	15	–	–	
Channel Separation 10 kHz ≤ f ≤ 20 kHz, Input Referenced	CS	–	–120	–	–	–120	–	–	–120	–	–	–120	–	–	–120	–	dB
Common Mode Rejection, R_S ≤ 10 kΩ	CMR	70	85	–	65	70	–	65	70	–	50	70	–	50	70	–	dB
Power Supply Rejection	PSR	65	100	–	65	100	–	65	100	–	50	100	–	50	100	–	dB

2. LM224: T_{low} = –25°C, T_{high} = +85°C
   LM324/LM324A: T_{low} = 0°C, T_{high} = +70°C
   LM2902: T_{low} = –40°C, T_{high} = +105°C
   LM2902V & NCV2902: T_{low} = –40°C, T_{high} = +125°C
   NCV2902 is qualified for automotive use.
3. The input common mode voltage or either input signal voltage should not be allowed to go negative by more than 0.3 V. The upper end of the common mode voltage range is V_{CC} –1.7 V.
4. Guaranteed by design.

ELECTRICAL CHARACTERISTICS (V_{CC} = 5.0 V, V_{EE} = Gnd, T_A = 25°C, unless otherwise noted.)

Characteristics	Symbol	LM224			LM324A			LM324			LM2902			LM2902V/NCV2902			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Output Voltage– High Limit (T_A = T_{high} to T_{low}) (Note 5)	V_{OH}																V
V_{CC} = 5.0 V, R_L = 2.0 kΩ, T_A = 25°C		3.3	3.5	–	3.3	3.5	–	3.3	3.5	–	3.3	3.5	–	3.3	3.5	–	
V_{CC} = 30 V (26 V for LM2902, V), R_L = 2.0 kΩ		26	–	–	26	–	–	26	–	–	22	–	–	22	–	–	
V_{CC} = 30 V (26 V for LM2902, V), R_L = 10 kΩ		27	28	–	27	28	–	27	28	–	23	24	–	23	24	–	
Output Voltage – Low Limit, V_{CC} = 5.0 V, R_L = 10 kΩ, T_A = T_{high} to T_{low} (Note 5)	V_{OL}	–	5.0	20	–	5.0	20	–	5.0	20	–	5.0	100	–	5.0	100	mV
Output Source Current (V_{ID} = +1.0 V, V_{CC} = 15 V)	I_{O+}																mA
T_A = 25°C		20	40	–	20	40	–	20	40	–	20	40	–	20	40	–	
T_A = T_{high} to T_{low} (Note 5)		10	20	–	10	20	–	10	20	–	10	20	–	10	20	–	
Output Sink Current	I_{O-}																mA
(V_{ID} = –1.0 V, V_{CC} = 15 V) T_A = 25°C		10	20	–	10	20	–	10	20	–	10	20	–	10	20	–	
T_A = T_{high} to T_{low} (Note 5)		5.0	8.0	–	5.0	8.0	–	5.0	8.0	–	5.0	8.0	–	5.0	8.0	–	
(V_{ID} = –1.0 V, V_O = 200 mV, T_A = 25°C)		12	50	–	12	50	–	12	50	–	–	–	–	–	–	–	μA
Output Short Circuit to Ground (Note 6)	I_{SC}	–	40	60	–	40	60	–	40	60	–	40	60	–	40	60	mA
Power Supply Current (T_A = T_{high} to T_{low}) (Note 5)	I_{CC}																mA
V_{CC} = 30 V (26 V for LM2902, V), V_O = 0 V, R_L = ∞		–	–	3.0	–	1.4	3.0	–	–	3.0	–	–	3.0	–	–	3.0	
V_{CC} = 5.0 V, V_O = 0 V, R_L = ∞		–	–	1.2	–	0.7	1.2	–	–	1.2	–	–	1.2	–	–	1.2	

5. LM224: T_{low} = –25°C, T_{high} = +85°C
   LM324/LM324A: T_{low} = 0°C, T_{high} = +70°C
   LM2902: T_{low} = –40°C, T_{high} = +105°C
   LM2902V & NCV2902: T_{low} = –40°C, T_{high} = +125°C
   NCV2902 is qualified for automotive use.
6. The input common mode voltage or either input signal voltage should not be allowed to go negative by more than 0.3 V. The upper end of the common mode voltage range is V_{CC} –1.7 V.

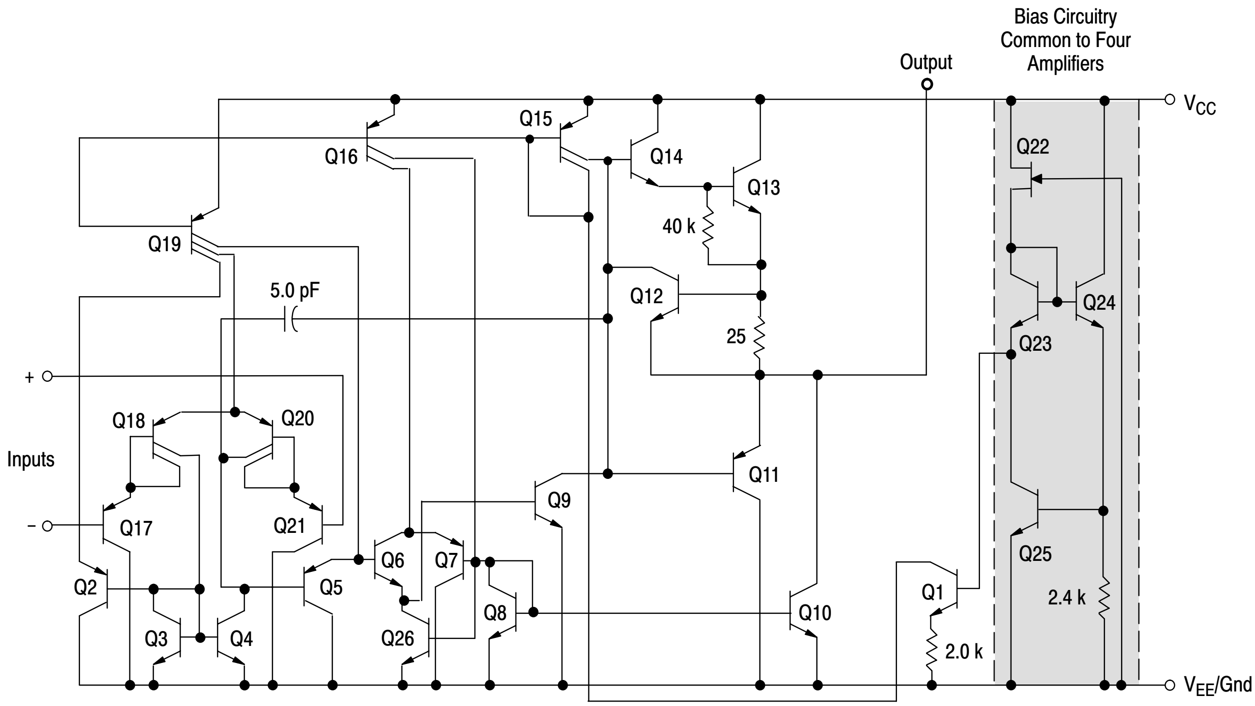


Figure 1. Representative Circuit Diagram
(One–Fourth of Circuit Shown)

CIRCUIT DESCRIPTION

The LM324 series is made using four internally compensated, two–stage operational amplifiers. The first stage of each consists of differential input devices Q20 and Q18 with input buffer transistors Q21 and Q17 and the differential to single ended converter Q3 and Q4. The first stage performs not only the first stage gain function but also performs the level shifting and transconductance reduction functions. By reducing the transconductance, a smaller compensation capacitor (only 5.0 pF) can be employed, thus saving chip area. The transconductance reduction is accomplished by splitting the collectors of Q20 and Q18. Another feature of this input stage is that the input common mode range can include the negative supply or ground, in single supply operation, without saturating either the input devices or the differential to single–ended converter. The second stage consists of a standard current source load amplifier stage.

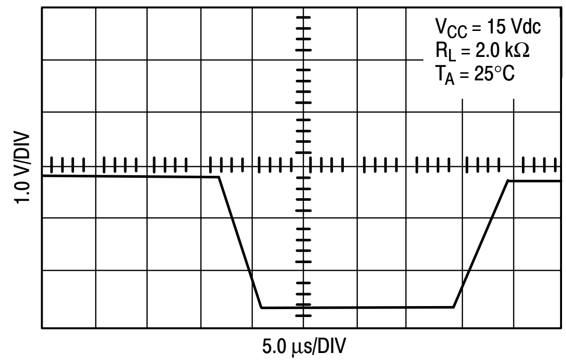
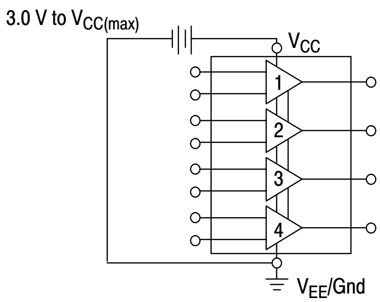
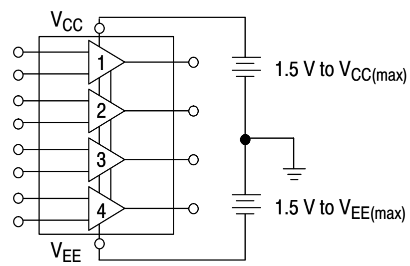


Figure 2. Large Signal Voltage Follower Response

Each amplifier is biased from an internal–voltage regulator which has a low temperature coefficient thus giving each amplifier good temperature characteristics as well as excellent power supply rejection.



Single Supply



Split Supplies

Figure 3.

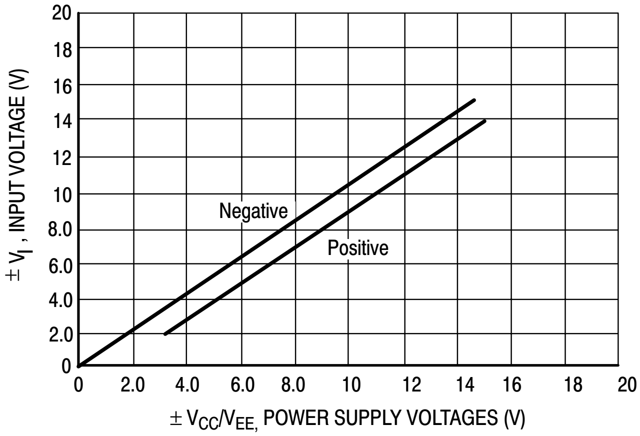


Figure 4. Input Voltage Range

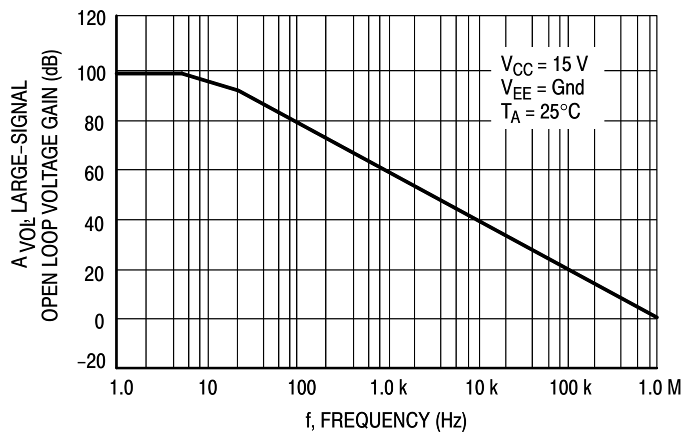


Figure 5. Open Loop Frequency

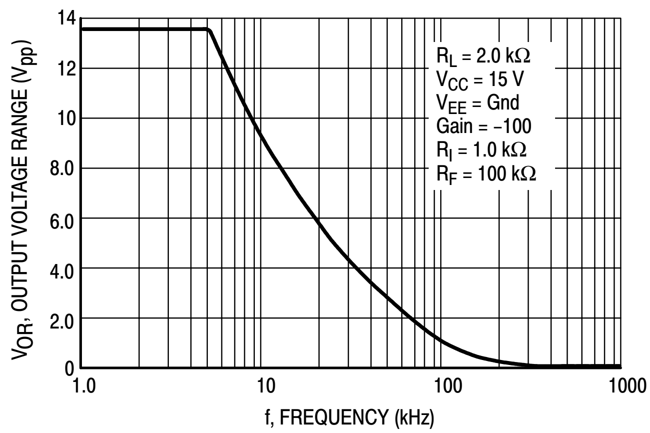


Figure 6. Large–Signal Frequency Response

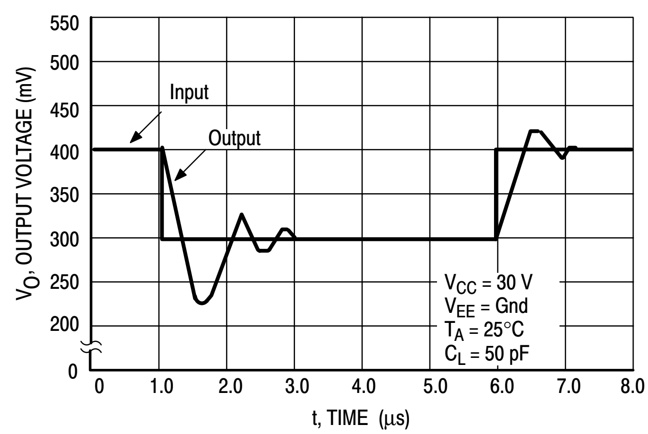


Figure 7. Small–Signal Voltage Follower Pulse Response (Noninverting)

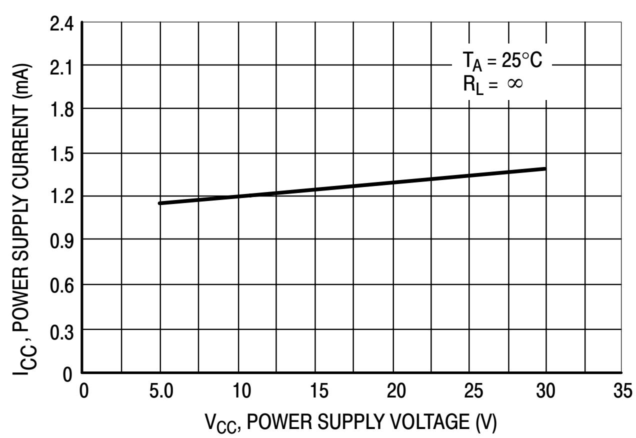


Figure 8. Power Supply Current versus Power Supply Voltage

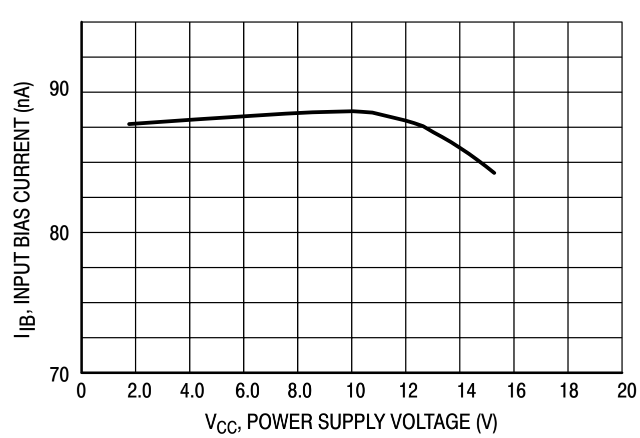


Figure 9. Input Bias Current versus Power Supply Voltage

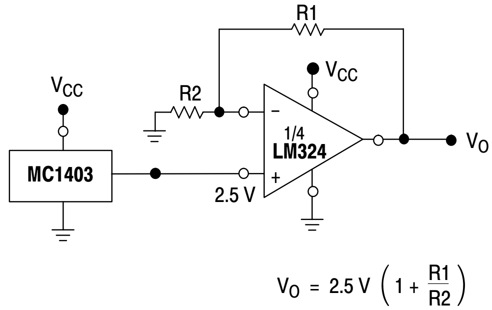


Figure 10. Voltage Reference

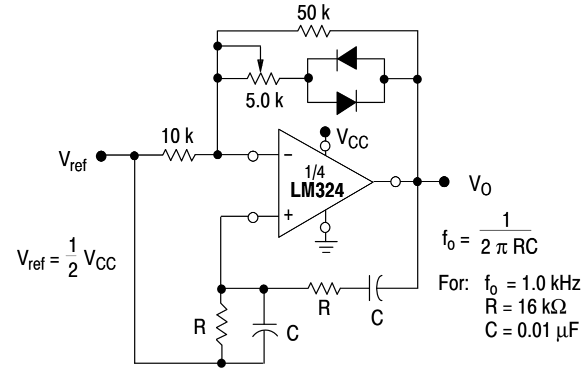


Figure 11. Wien Bridge Oscillator

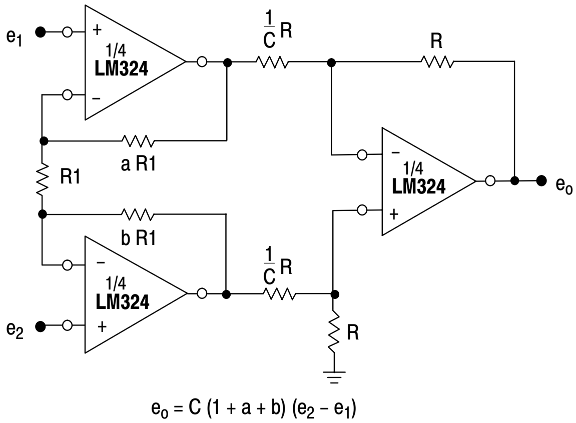


Figure 12. High Impedance Differential Amplifier

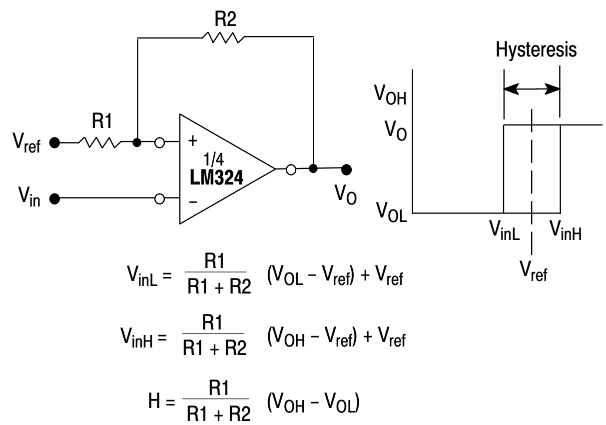


Figure 13. Comparator with Hysteresis

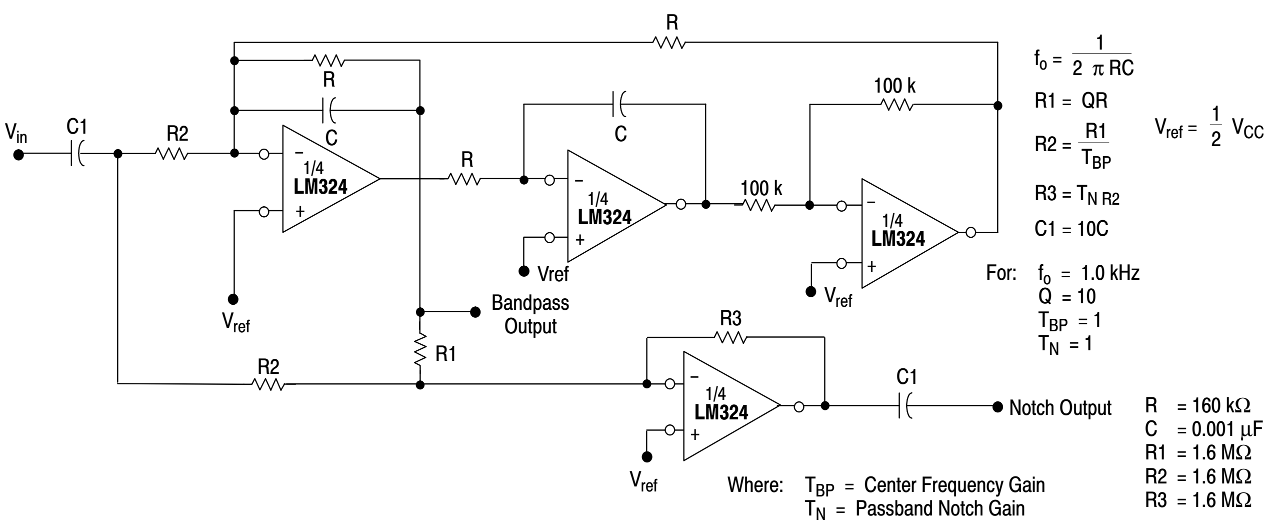
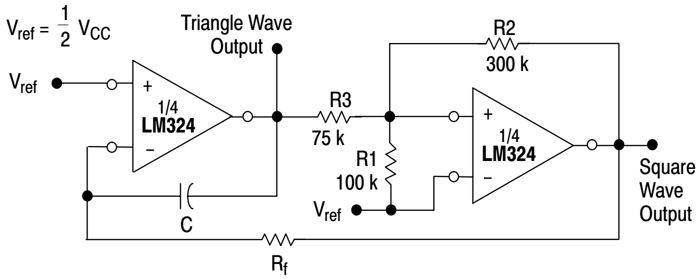


Figure 14. Bi–Quad Filter



$$f = \frac{R1 + R_C}{4\ CR_f\ R1} \qquad \text{if} \quad R3 = \frac{R2\ R1}{R2 + R1}$$

Figure 15. Function Generator

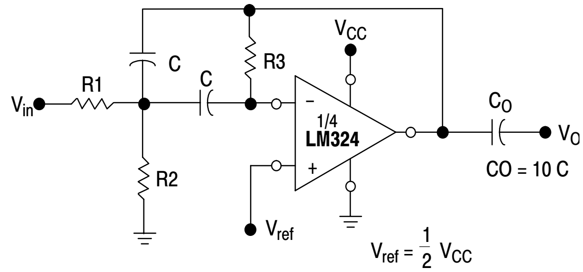


Figure 16. Multiple Feedback Bandpass Filter

Given: f_o = center frequency
$A(f_o)$ = gain at center frequency

Choose value f_o, C

Then: $R3 = \frac{Q}{\pi\ f_o\ C}$

$R1 = \frac{R3}{2\ A(f_o)}$

$R2 = \frac{R1\ R3}{4Q^2\ R1 - R3}$

For less than 10% error from operational amplifier, $\frac{Q_o\ f_o}{BW} < 0.1$

where f_o and BW are expressed in Hz.

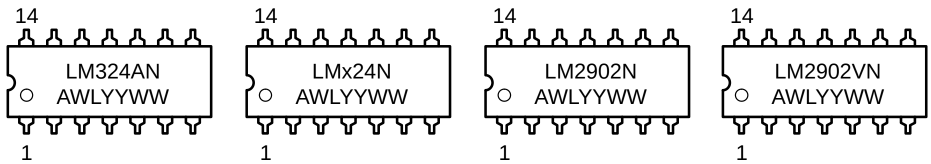
If source impedance varies, filter may be preceded with voltage follower buffer to stabilize filter parameters.

ORDERING INFORMATION

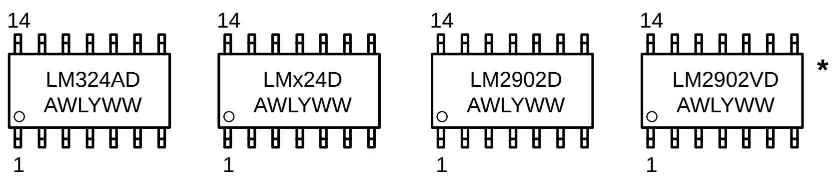
Device	Package	Operating Temperature Range	Shipping
LM224D	SO–14	–25° to +85°C	55 Units/Rail
LM224DR2	SO–14		2500 Tape & Reel
LM224DTB	TSSOP–14		96 Units/Rail
LM224DTBR2	TSSOP–14		2500 Tape & Reel
LM224N	PDIP–14		25 Units/Rail
LM324D	SO–14	0° to +70°C	55 Units/Rail
LM324DR2	SO–14		2500 Tape & Reel
LM324DTB	TSSOP–14		96 Units/Rail
LM324DTBR2	TSSOP–14		2500 Tape & Reel
LM324N	PDIP–14		25 Units/Rail
LM324AD	SO–14		55 Units/Rail
LM324ADR2	SO–14		2500 Tape & Reel
LM324ADTB	TSSOP–14		96 Units/Rail
LM324ADTBR2	TSSOP–14		2500 Tape & Reel
LM324AN	PDIP–14		25 Units/Rail
LM2902D	SO–14	–40° to +105°C	55 Units/Rail
LM2902DR2	SO–14		2500 Tape & Reel
LM2902DTB	TSSOP–14		96 Units/Rail
LM2902DTBR2	TSSOP–14		2500 Tape & Reel
LM2902N	PDIP–14		25 Units/Rail
LM2902VD	SO–14	–40° to +125°C	55 Units/Rail
LM2902VDR2	SO–14		2500 Tape & Reel
LM2902VDTB	TSSOP–14		96 Units/Rail
LM2902VDTBR2	TSSOP–14		2500 Tape & Reel
LM2902VN	PDIP–14		25 Units/Rail
NCV2902DR2	SO–14		2500 Tape & Reel

MARKING DIAGRAMS

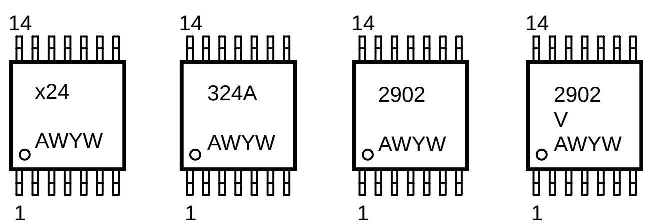
PDIP–14
N SUFFIX
CASE 646



SO–14
D SUFFIX
CASE 751A



TSSOP–14
DTB SUFFIX
CASE 948G

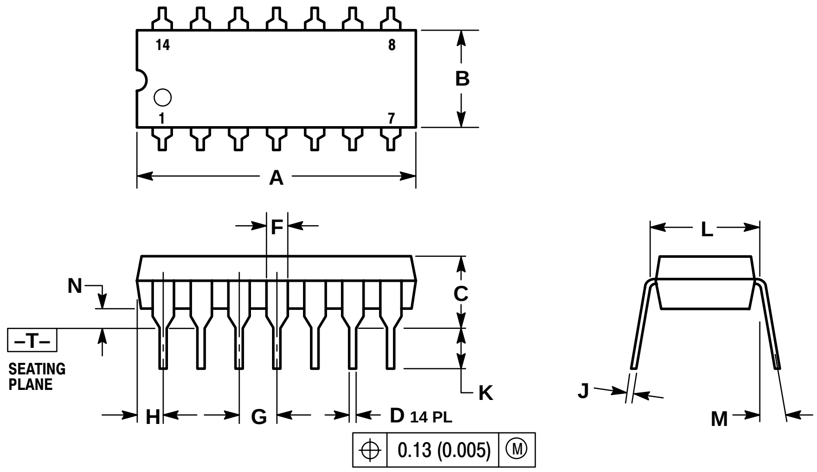


x = 2 or 3
A = Assembly Location
WL = Wafer Lot
YY, Y = Year
WW, W = Work Week

*This marking diagram also applies to NCV2902.

PACKAGE DIMENSIONS

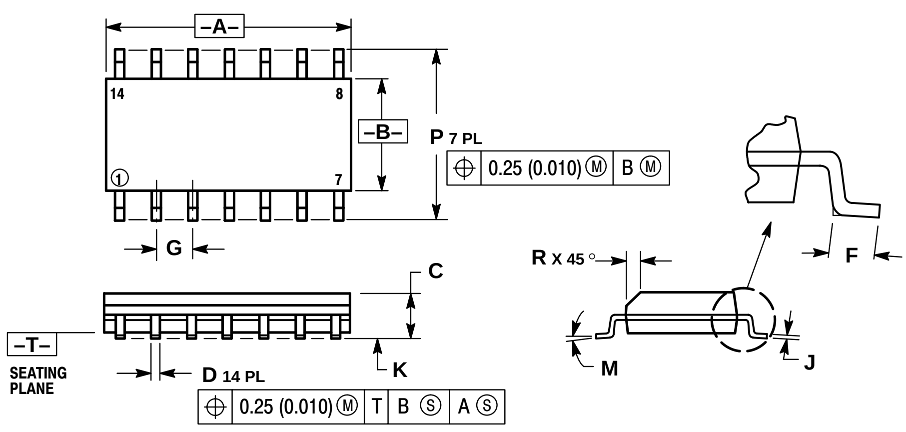
PDIP–14
N SUFFIX
CASE 646–06
ISSUE M



NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. DIMENSION L TO CENTER OF LEADS WHEN FORMED PARALLEL.
4. DIMENSION B DOES NOT INCLUDE MOLD FLASH.
5. ROUNDED CORNERS OPTIONAL.

	INCHES		MILLIMETERS	
DIM	MIN	MAX	MIN	MAX
A	0.715	0.770	18.16	18.80
B	0.240	0.260	6.10	6.60
C	0.145	0.185	3.69	4.69
D	0.015	0.021	0.38	0.53
F	0.040	0.070	1.02	1.78
G	0.100 BSC		2.54 BSC	
H	0.052	0.095	1.32	2.41
J	0.008	0.015	0.20	0.38
K	0.115	0.135	2.92	3.43
L	0.290	0.310	7.37	7.87
M	---	10°	---	10°
N	0.015	0.039	0.38	1.01

SO–14
D SUFFIX
CASE 751A–03
ISSUE F

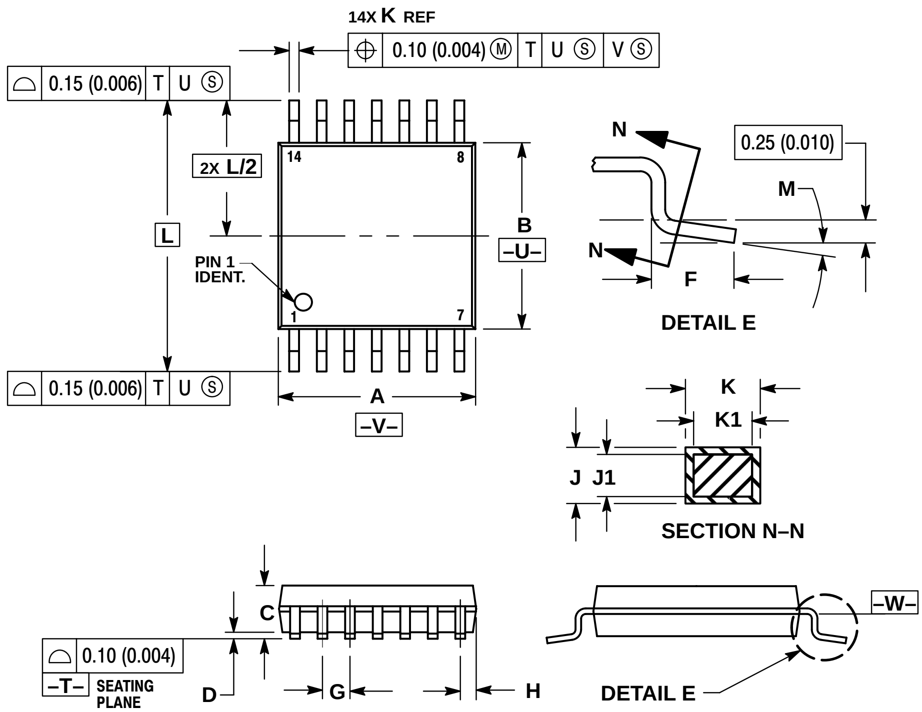


NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: MILLIMETER.
3. DIMENSIONS A AND B DO NOT INCLUDE MOLD PROTRUSION.
4. MAXIMUM MOLD PROTRUSION 0.15 (0.006) PER SIDE.
5. DIMENSION D DOES NOT INCLUDE DAMBAR PROTRUSION. ALLOWABLE DAMBAR PROTRUSION SHALL BE 0.127 (0.005) TOTAL IN EXCESS OF THE D DIMENSION AT MAXIMUM MATERIAL CONDITION.

	MILLIMETERS		INCHES	
DIM	MIN	MAX	MIN	MAX
A	8.55	8.75	0.337	0.344
B	3.80	4.00	0.150	0.157
C	1.35	1.75	0.054	0.068
D	0.35	0.49	0.014	0.019
F	0.40	1.25	0.016	0.049
G	1.27 BSC		0.050 BSC	
J	0.19	0.25	0.008	0.009
K	0.10	0.25	0.004	0.009
M	0°	7°	0°	7°
P	5.80	6.20	0.228	0.244
R	0.25	0.50	0.010	0.019

PACKAGE DIMENSIONS

TSSOP–14
DTB SUFFIX
CASE 948G–01
ISSUE O



NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: MILLIMETER.
3. DIMENSION A DOES NOT INCLUDE MOLD FLASH, PROTRUSIONS OR GATE BURRS. MOLD FLASH OR GATE BURRS SHALL NOT EXCEED 0.15 (0.006) PER SIDE.
4. DIMENSION B DOES NOT INCLUDE INTERLEAD FLASH OR PROTRUSION. INTERLEAD FLASH OR PROTRUSION SHALL NOT EXCEED 0.25 (0.010) PER SIDE.
5. DIMENSION K DOES NOT INCLUDE DAMBAR PROTRUSION. ALLOWABLE DAMBAR PROTRUSION SHALL BE 0.08 (0.003) TOTAL IN EXCESS OF THE K DIMENSION AT MAXIMUM MATERIAL CONDITION.
6. TERMINAL NUMBERS ARE SHOWN FOR REFERENCE ONLY.
7. DIMENSION A AND B ARE TO BE DETERMINED AT DATUM PLANE –W–.

	MILLIMETERS		INCHES	
DIM	MIN	MAX	MIN	MAX
A	4.90	5.10	0.193	0.200
B	4.30	4.50	0.169	0.177
C	---	1.20	---	0.047
D	0.05	0.15	0.002	0.006
F	0.50	0.75	0.020	0.030
G	0.65 BSC		0.026 BSC	
H	0.50	0.60	0.020	0.024
J	0.09	0.20	0.004	0.008
J1	0.09	0.16	0.004	0.006
K	0.19	0.30	0.007	0.012
K1	0.19	0.25	0.007	0.010
L	6.40 BSC		0.252 BSC	
M	0°	8°	0°	8°

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